

Final Report

Title: Three-dimensional kinetic simulation of the nonlinear evolution of lower-hybrid waves in the auroral plasma

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Under this grant we have done research on the following topics. A brief summary of our findings and resulting publications are given.

1. Development of Parallel PIC Codes (PPIC)

Three-dimensional kinetic simulations of plasma waves are possible only if parallel computing techniques are applied to particle-in-cell simulations of plasmas. Having realized this we set forth on developing such codes. The end result is that we have state-of-the-art 3-D PIC codes. In our recent effort we have made the code portable from machine to machine without much hassle. Publications #1-3 are related to this effort.

2. Evolution of Lower-Hybrid Pump Waves

We utilized the PPIC code to study the evolution of long wavelength lower pump waves. Such pump waves have fast phase velocities and therefore they do not interact with cold ionospheric ions. Our simulations showed that such fast waves undergo parametric decay generating slower and slower waves, which eventually interact with ions and accelerate them perpendicular to the ambient magnetic field. The electrons are also accelerated generating a magnetic field-aligned tail in the velocity distribution extending up to twice the parallel phase velocity of the pump waves.

In the processes of the parametric decay, the plasma density is highly perturbed generating both density enhancements and depletions, which are narrow across the magnetic field lines and are quite extended parallel to it. These results are described in publication #4 and #5.

3. Electron-beam Driven Plasma Electrodynamics

In the auroral plasma electron beams are the most effective source of generating plasma waves, including the lower-hybrid waves. An electron beam drives a rich variety of plasma phenomena, many of which have been measured, in the auroral plasma. One obvious question is about the conditions under which an electron beam drives the lower hybrid waves. This study has been performed using (i) one-dimensional Vlasov simulations of double layers and (ii) 3-D PPIC code.

Using the Vlasov simulations of double layers, we showed that a field-aligned potential drop occurs in the form of a double layer, *which anchors itself in a plasma cavity*. Since plasma cavities are a common feature of the auroral plasma, our simulations suggest that strong parallel electric fields should be detected in density cavities. We also found that in response to an applied potential, a natural response of a plasma is to generate counterstreaming electron populations as measured by FAST. The counterstreaming is generated in an expanding potential ridge on the top of a double layer resulting from the different responses of electrons and ions to an applied parallel electric field.

Our Vlasov simulations also revealed that electron holes are a common feature of the high potential side of a strong double layer. The formation and dynamics of such electron holes were compared against the measurements from FAST. These results were presented at the 1999 AGU Fall Meeting and are partly summarized in a recent publication, #7 in the publication list.

Our 3-D PPIC simulations of a plasma have yielded a wealth of information on nonlinear plasma dynamics driven by an electron beam. Unfortunately due to limited funding the work was slowed down, and the results have not been published yet. In a recent paper we have studied the 3-D structure of electron holes and their stability. The results from this study are compared against the observations from FAST and also against 2-D simulations available in the literature. The study is continued under a NSF grant. The relevant publications from this 3-D study are publications #7-9.

4. Studies on Inertial and Kinetic Alfvén Waves:

One of the sources of energy input into the auroral plasma is the Alfvén wave. There are now several observations indicating that the auroral electron beams might be accelerated by the parallel electric field associated with kinetic Alfvén waves. In order to close the loop consisting of Alfvén waves, electron beams, and auroral plasma waves, and particle acceleration, we started an effort on synthesizing these phenomena. In this direction, our first attempt was to study the linear properties of shear and kinetic Alfvén waves including both inertial and warm plasma effects. We showed that both these types of Alfvén waves show the phenomenon of resonance cone. The waves radiated by sources, which are narrow across the magnetic field, propagate within a cone of a few milliradians, and within the cone the waves have a characteristic interference structure determined by the Airy function. The ponderomotive force associated with the Airy function pattern can generate density structure in the Alfvén waves as measured by Freja. The results of this study was published in publication #10. We had proposed to perform further research on this synthesis effort, but NASA did not fund the proposal.

Another outgrowth of this effort was to develop fully 3-D electromagnetic PPPIC code. We are applying this code to study the reconnection problem (publication #11).

In addition to the research reported above, the support under the grant proved invaluable in educational terms. Two Ph.D. dissertations and one MS thesis were a direct result of this research effort. These dissertations and thesis are listed. In addition to the graduate education leading to Ph.D. and MS thesis research, the PIC codes developed here are found to be extremely useful in both graduate and undergraduate classes on parallel computing. These PIC codes have become an instructional tool in our computer engineering curriculum at the University of Alabama in Huntsville.

Publications:

1. Abdelmageed Elsadek, Saleh Al-Sharaeh, Safwat Elnahass, Nagendra Singh, and B. Earl Wells, Parallel Implementations of a Three-Dimensional PIC code Plasma Simulation, in Proceedings of the ISCA 11th International Conference on Parallel and Distributed Computing Systems, Chicago, IL, September 2-4, 1998.
2. Al-Sharaeh, S. H., A. Abdelrazek, B. Earl Wells, Nagendra Singh, Massively parallel particle-in-cell technique for the three-dimensional simulation of plasma phenomena, *Proceedings of the ISCA Ninth International Conference on Parallel and Distributed Computing Systems (PDCS)*, Dijon, France, September 25-27, 1996, pp. 548-553.
3. Sin Ming Loo, B. Earl Wells, Nagendra Singh, and Edith P. Huang, Case Study: A Portable Parallel Particle-in-cell Code simulation, *Proceedings of the International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA' 98)*, Las Vegas, Nevada, July 13-16, 1999, pp. 1488-1494.
4. N. Singh, B. Earl Wells, A. Abdelrazek, S. Al-Sharaeh, W. C. Leung, Three dimensional kinetic simulation of the nonlinear evolution of lower hybrid pump waves, *J. Geophys. Res.* **103**, 9333-9349, 1998.
5. Singh, N., S. Al-Sharaeh, A. Abdelrazek, W. C. Leung, and B. E. Wells, Three-dimensional numerical simulation of ion and electron acceleration by parametric decay of fast lower hybrid waves, *Geophys. Res. Lett.* **23**, 3663, 1996.
6. Singh, N., Consequences of Parallel Electric Fields Applied to a Plasma with Density Cavities, AGU Fall Meeting, San Francisco, Dec. 1999.
7. Singh, N., Electron holes as a common feature of plasma waves driven by a double layer, in press, *Geophys. Res. Lett.*, 2000.

8. Loo, S. M., N. Singh, and B. E. Wells, Evolution of Electron-beam Generated Waves Resulting in Transverse Ion Heating and Filamentation of Plasma Density, AGU Fall Meeting, San Francisco, Dec. 1999.
9. Singh, N., S. M. Loo, B. Earl Wells, and C. Deverapalli, Three-dimensional structure of electron holes driven by an electron beam, *Geophys. Res. Lett.*, under revision, 2000.
10. Singh, N., Field patterns of Alfvén wave resonance cones, *J. Geophys. Res.* 104, p. 6999, 1999.
11. Saha, S., and N. Singh, Evolution of a Plasma to the Harris Equilibrium, AGU Fall Meeting, San Francisco, Dec. 1999.

Dissertations and Thesis:

1. Saleh Hosni Al-Sharaeh, Dissertation Title: "A Massively Parallel Particle-in-Cell Technique for a Three Dimensional Simulation of Plasma Phenomena," The University of Alabama in Huntsville, Huntsville, Alabama, December 1996.
2. Abdelrazek Abdelmageed Elsadek, Dissertation Title: "New Functional and Data Parallel Methodologies for the Efficient Distributed Processing of Large-scale Applications," The University of Alabama in Huntsville, Huntsville, Alabama, August 1997.
3. Sin Ming Loo, MS Thesis Title: "Portable Parallel Particle-In-Cell Plasma Code," The University of Alabama in Huntsville, Huntsville, Alabama, May 2000.

